

# Analysis of Containment Volume Effect on the Pressure and Temperature during LOCA in the AP1000 Reactor Containment

Farzad Choobdar Rahim<sup>1, 2\*</sup>

<sup>1</sup>Department of Mechanical Engineering, Urmia University, Urmia, West Azerbaijan, Iran

<sup>2</sup>Faculty of Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

farzad\_choobdar@yahoo.com

**Abstract-** With many years in high pressure systems and technology, pipe break still occurs. The occurrence of this event and analysis of it in a PWR reactor is too important, absolutely in the highest grade of danger in double ended guillotine type of break. In this paper containment volume has been changed, and then variation of pressure and temperature of containment with time has been analyzed. This simulation is done with a hand-made computer code. At last, the results of simulation are compared with plant reports.

**Keywords-** AP1000 Reactor; Containment; LOCA; Two Phases; Heat Transfer; Change of Volume

## I. INTRODUCTION

Westinghouse Electric Company, the pioneer in nuclear energy, once again sets a new industry standard with the AP1000. The AP1000 is the safest and most economical nuclear power plant available in the worldwide commercial marketplace, and is the only Generation III+ reactor to receive Design Certification from the U.S. Nuclear Regulatory Commission (NRC). The established design of the AP1000 offers three distinct advantages over other designs: unequaled safety, economic competitiveness and improved and more efficient operations. Simplification is a major design objective of the AP1000. Simplifications in overall safety systems, normal operating systems, the control room, construction techniques, and instrumentation and control systems provide a plant that is easier and less expensive to build, operate, and maintain. Plant simplifications yield fewer components, cable, and seismic building volume, all of which contribute to considerable savings in capital investment and lower operation and maintenance costs.

At the same time, the safety margins for AP1000 have been increased dramatically over currently operating plants. The containment vessel is of high integrity, a freestanding steel structure with a wall thickness of 1.75 inches (4.44 cm). The containment is 130 feet (39.6 m) in diameter. The ring sections and vessel heads are constructed of steel plates pre-formed in an off-site fabrication facility and shipped to the site for assembly and installation using a large-capacity crane. The primary containment prevents the uncontrolled release of radioactivity to the environment. It has a design leakage rate of 0.10 percent weight per day of the containment air during a design basis accident and the

resulting containment isolation. The AP1000 containment contains a 16-foot (4.9m) diameter main equipment hatch and a personnel airlock at the operating-deck level, and a 16-foot (4.9m) diameter maintenance hatch and a personnel airlock at grade level. These large hatches significantly improve accessibility to the containment during outages and, consequently, reduce the potential for congestion at the containment entrances. These containment hatches, located at the two different levels, allow activities occurring above the operating deck to be unaffected by activities occurring below the operating deck. The containment arrangement provides significantly larger lay-down areas than most conventional plants at both the operating deck level and the maintenance floor level. Ample lay-down space is provided for staging of equipment and personnel, equipment removal paths, and space to accommodate remotely operated service equipment and mobile units.

Access platforms and lifting devices are provided at key locations, as are service provisions such as electrical power, demineralized water, breathing and service air, ventilation and lighting. Concrete Shield Building—the AP1000 containment design incorporates a shield building that surrounds the containment vessel and forms the natural convection annulus for containment cooling. This building is a cylindrical, reinforced concrete structure with a conical roof that supports the water storage tank and air diffuser (or chimney) of the passive containment cooling system (PCS). It shares a common base mat with the primary containment and auxiliary building, and is designed as a seismic Category 1 structure. It has an inner diameter of about 140 feet (43m), a height of 73.25 ft (22 m), and a wall thickness of 3 ft (0.9 m) in the cylindrical section. The two primary functions of the shield building during normal operation are 1) to provide an additional radiological barrier for radioactive systems and components inside the containment vessel and 2) to protect the containment vessel from external events, such as tornados and tornado-driven objects that might impinge on it. As described earlier, under design-basis accident conditions, the shield building serves as a key component of the PCS by aiding in the natural convective cooling of the containment [1]. In this paper, one of the most dangerous accidents in reactor containments known as Loss of Coolant Accident (LOCA) in its worst condition called large LOCA has been modeled. The specific type of large

LOCA is DECL (Double Ended Cold Leg) break which means a total guillotine type of break in cold leg pipe. When LOCA occurs, the coolant itself is lost, then in this case that happens with pipe break or any kind of losing, the danger of core melting is possible. This modeling is performed in single volume method. Fig. 1 shows the containment and the constitutive components of AP1000 containment cooling systems:

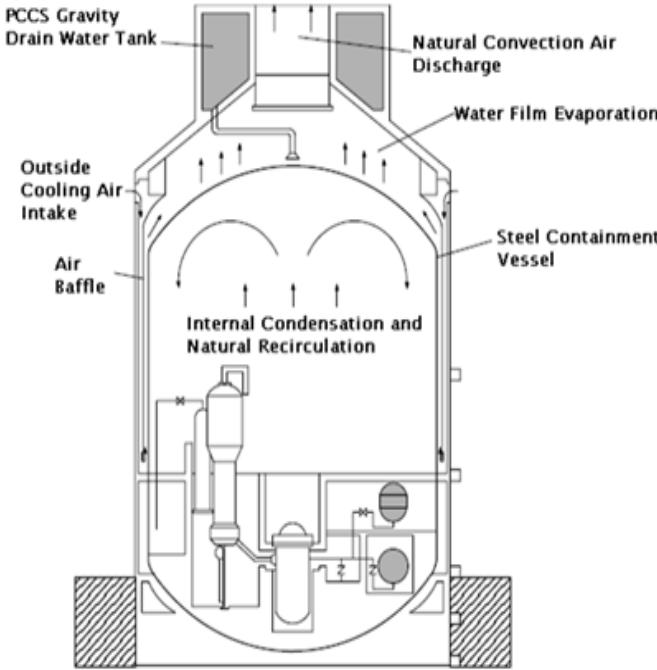


Fig. 1 AP1000 passive containment cooling system

## II. MATHEMATICAL FORMULATION

In the analysis of Transient Conditions, using the application of the first law of thermodynamics in three subsections including containment air, water vapor initially in the air of containment, and discharged water into the containment from primary system are shown as following [2]:

$$\frac{d(m_a u_a)}{dt} = \dot{Q}_{wc_1-a} + \dot{Q}_{wpd-a} - \dot{Q}_{a-st} - p_T \frac{dV_a}{dt} \quad (1)$$

$$\frac{d(m_{wc_1} u_{wc_1})}{dt} = \dot{Q}_{wpd-wc_1} - \dot{Q}_{wc_1-a} - \dot{Q}_{wc_1-st} - p_T \frac{dV_{wc_1}}{dt} \quad (2)$$

$$\frac{d(m_{wpd} u_{wpd})}{dt} = \dot{Q}_{wpd} - \dot{Q}_{wpd-wc_1} - \dot{Q}_{wpd-a} - \dot{Q}_{wpd-st} - p_T \frac{dV_{wpd}}{dt} \quad (3)$$

And ultimately adding them up together, the following equation is obtained:

$$\begin{aligned} \frac{d}{dt} (m_a u_a + m_{wc_1} u_{wc_1} + m_{wpd} u_{wpd}) \\ = \dot{Q}_{wpd} - \sum_i \dot{Q}_{i-st} - p_T \frac{d(V_a + V_{wc_1} + V_{wpd})}{dt} \end{aligned} \quad (4)$$

Whereas volume of containment is constant, therefore,

$$\frac{d(V_a + V_{wc_1} + V_{wpd})}{dt} = 0 \quad (5)$$

Equation (4) can be rewritten to express the water conditions separately as primary water and water in air:

$$\begin{aligned} x_{st1}^{t+\Delta t} (u_{fg}^{t+\Delta t} (m_{wpd}^{t+\Delta t} + m_{wa}^t)) = \\ Q_{wpd}^{t+\Delta t} - Q_{c-st}^{t+\Delta t} - m_a C_{va} (T^{t+\Delta t} - T_a^t) \\ - m_{wpd}^{t+\Delta t} (u_f^{t+\Delta t} - u_{wp}^t) - m_{wa}^t (u_f^{t+\Delta t} - u_{wa}^t) \end{aligned} \quad (6)$$

$Q_{wpd}^{t+\Delta t}$  is produced by input mass flow to the containment,  $Q_{wpd}^{t+\Delta t} = \dot{m}_{wpd}^{t+\Delta t} h^{t+\Delta t} \Delta t$  and  $Q_{c-st}^{t+\Delta t}$  has been modeled in heat transfer section. By introducing the definition of the steam static quality ( $x_{st}$ ) in the containment and treating air as a perfect gas, then:

$$x_{st2}^{t+\Delta t} = \frac{\frac{V_T^{t+\Delta t}}{m_w^{t+\Delta t}} - V_f^{t+\Delta t}}{V_{fg}^{t+\Delta t}} \quad (7)$$

Now, all the unknown parameters depend on  $T^{t+\Delta t}$ ; then with conjecture of this value and checking it, all of the unknown variables can be determined. If the absolute difference of static qualities which are already denoted ( $x_{st1}^{t+\Delta t}$  in Eq. 6 and  $x_{st2}^{t+\Delta t}$  in Eq. 7) is less than an error function, then other parameters in subsequent conditions will be determined. Air partial pressure is calculated by the perfect gas law for each cell is the following:

$$P_a = \frac{m_a R T_{sat}}{V_T} \quad (8)$$

And total pressure is the following:

$$p_t^{t+\Delta t} = p_w^{t+\Delta t} (T^{t+\Delta t}) + p_a^{t+\Delta t} \quad (9)$$

Where,  $p_t^{t+\Delta t}$  is the pressure of mixture (total pressure),  $p_w^{t+\Delta t}$  is partial pressure of the saturated water vapor corresponding to  $T^{t+\Delta t}$ ,  $p_a^{t+\Delta t}$  is partial pressure of air corresponding to  $T^{t+\Delta t}$ .

## III. HEAT TRANSFER

When an accident happens in the reactor containment, if the level of heat transfer is lower than the requirement level, it may cause the pressure of containment to become more than its designing pressure, so it ends the breakage of security containment and leads the radioactive materials to spread into air and pollute it. Therefore the reactors should be designed to have the maximum heat transfer when accident happens [3]. In this section, the correlations of heat flux and the convective heat transfer coefficient  $h_c$  in the Down-comer and Riser have been defined. In Fig. 2, heat transfers from Riser and Down-Comer are shown:

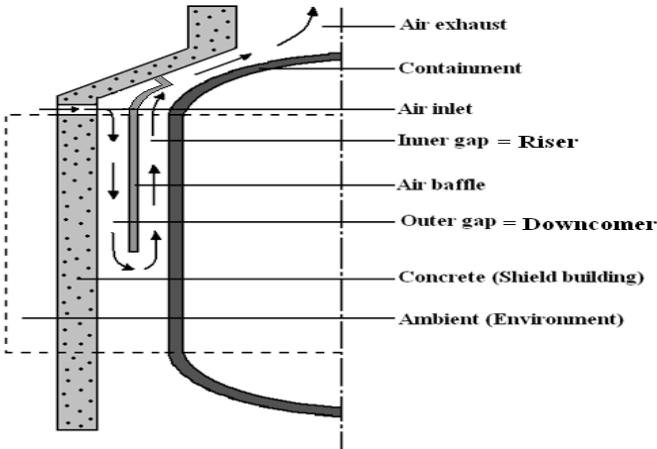


Fig. 2 System of air passes from Riser and Down-Comer

Heat flux in the Riser and Down-Comer are the following:

$$q = h_c (T_b - T_i) \quad (10)$$

where  $T_b$  is the wall temperature of Riser or Down-Comer and  $T_i$  is the air temperature. The using correlation for convective heat transfer coefficient  $h_c$  in the Riser and Down-Comer is based on the following relation:

$$h_c = \frac{k}{L} \left[ 0.037 \text{Re}^{\frac{4}{5}} \text{Pr}^{\frac{1}{3}} \right] \quad (11)$$

In the preceding equations,  $k$  is the coefficient of Air,  $L$  is the Length of the Riser or Down-Comer,  $\text{Re}$  is the Reynolds number and  $\text{Pr}$  is the Prandtl number [4].

#### IV. RESULTS

Modeling is performed by MATLAB software. Released mass flow and enthalpy are used as matrix from [5]. The main purpose is to determine the pressure and temperature variations with respect to time with changing containment volume. In the Table I, initial conditions of modeling and containment geometry are presented.

TABLE I CONTAINMENT GEOMETRY AND INITIAL CONDITIONS [1]

Internal Temperature (°C)	48
Pressure (MPa)	0.1082
Relative Humidity (%)	0
Net Free Volume ( $\text{m}^3$ )	58969.067
External Temperature (°C)	37.77
Broken Pipe Pressure (MPa)	15.9268
Broken Pipe Temperature (°C)	280.66

The following figures are generated from modeling. All materials used have been derived from [7]. In Figs. 3 and 4, pressure and temperature variations with respect to time in short term are shown. As it is observed, if the containment volume is smaller than actual volume at last, peak pressure and temperature increases; but when containment volume increases, peak pressure and temperature decreases.

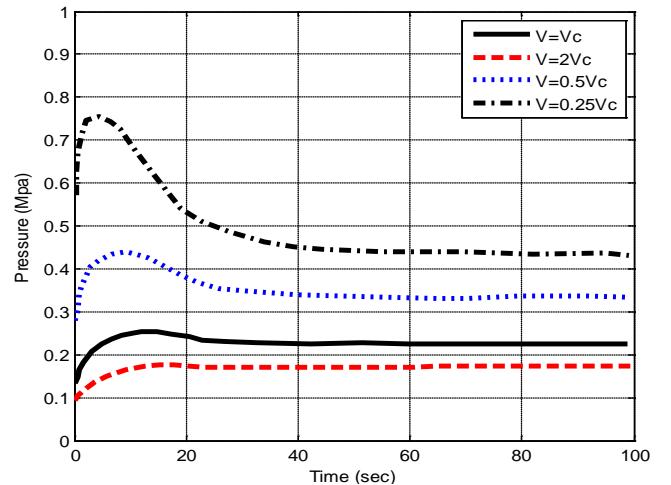


Fig. 3 Pressure variations with respect to time in short term

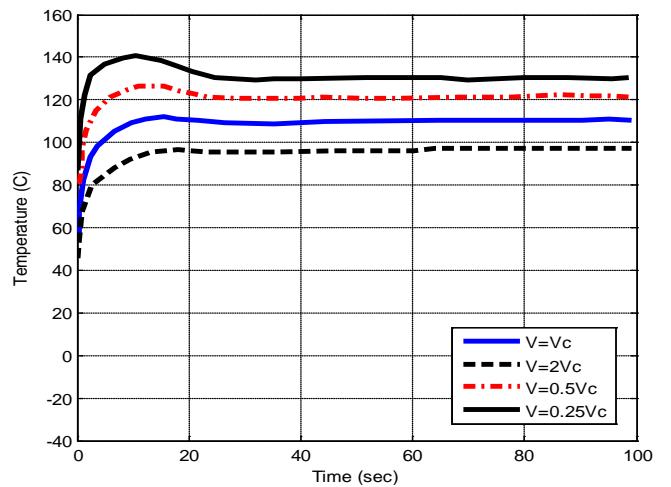


Fig. 4 Temperature variations with respect to time in short term

The variations of pressure and temperature of containment in the Long Term are shown in Figs. 5 and 6 respectively. As it can be observed, the pressure and temperature curves look similar with each other; therefore we can say they are proportional to each other. If the volume of containment increases to two-fold when LOCA accident happens, the containment will be safe.

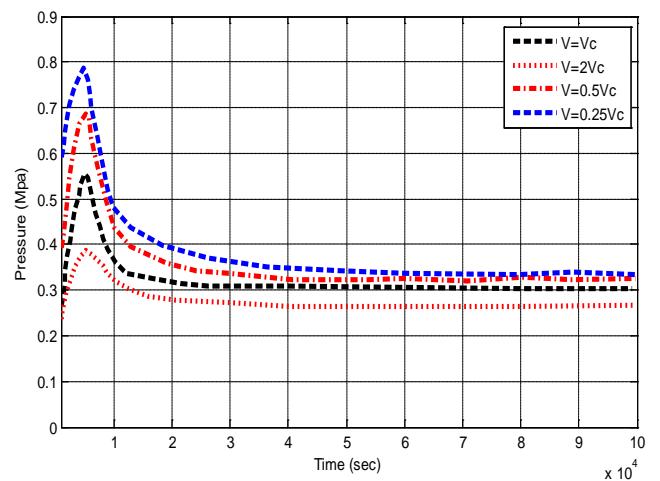


Fig. 5 Time variations of pressure in long term

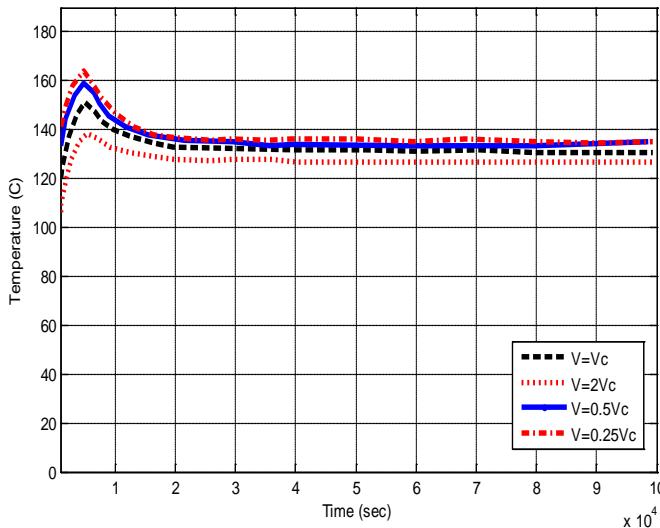


Fig. 6 Time variations of temperature in long term

In Table II, brief results have been shown with differences between model and report [8]. As it is shown

from results indicated in the Table II, there is a very good agreement between our results and the results in [8].

## V. CONCLUSIONS

Comparison between model result and report result shows that, two phases (water plus steam) simulation of this accident in AP1000 with single volume method is acceptable. Because of differences between consequences of modeling and report, it can be inferred to ignore mathematical procedures. Conjectures in transients and equilibrium conditions with receivable assumptions are useful approximations for AP1000 systems. In the long term conditions, peak of pressures and temperature in the states of 0.25, 0.5 and 1 fold containment volume are over design pressure (0.49MPa) [9], but in the 2 fold volume of containment, pressure and temperature peaks is under design pressure. This verity makes it clear that the volume of containment is decreased, the safety is not possible, and the importance of passive safety systems is more prominent when LOCA accident happens.

TABLE II SUMMARY OF RESULTS WITH DIFFERENCES BETWEEN MODEL AND REPORT [8]

	Break Pressure Peak in the Short Term (Mpa)	Pressure Peak in the LongTerm (Mpa)	Temperature Peak in the Short Term(°C)	Temperature Peak in the Long Term(°C)
Report [8]	---	0.49	--	140.5
<b>V=0.25Vc</b>	0.7554	0.7871	141.1	164.2
<b>V=0.5Vc</b>	0.4400	0.6863	126.4	159.2
<b>V=Vc</b>	0.2544	0.5531	111	151
<b>V=2Vc</b>	0.1419	0.3859	96.74	138.5

## NOMENCLATURE OF MATHEMATICAL FORMULATION AND HEAT TRANSFER

$m_a$  is the mass of containment air.

$m_{wc}$  is water vapor in the containment air.

$m_{wp}$  is water initially in the primary (or secondary) system depending on rupture assumption.

$m_{wpd}$  at any given time, of the mass  $m_{wp}$ , has discharged into the containment.

$V$  is the volume.

$V_c$  is the net free volume of containment.

$V_p$  is the volume of primary system.

$V_T$  is the total volume ( $V_c + V_p$ ).

$m_{wa}$  is the mass of water initially in the containment air.

$m_w$  is the mass of water, which is composed of water. Vapor initially in the air and water or water and steam initially in the failed system, i.e.,  $m_{wa} + m_{wp}$ .

$u = u(T, v)$  is the internal energy per unit mass defined with respect to a reference internal energy.

$u_w$  is the internal energy of the water in the containment air and the water in the failed system, i.e.,  $u_{wa}$  and  $u_{wp}$ .

$c_{va}$  is specific heat of air at constant volume.

$Q_{c-st}$  is heat transferred from control volume to structures (which is modeled in heat transfer).

$Q_{wpr-c}$  is heat transferred from water remaining of primary cycle to control volume.

$T_a$  is air temperature.

$T$  is temperature for the air/steam mixture in the containment.

$T_{sat}$  is the internal air/steam mixture temperature in the containment (it is equal to  $T$ ).

$p$  is the pressure of mixture.

$p_w$  is partial pressure of the saturated water vapor corresponding to  $T$ .

$p_a$  is partial pressure of air corresponding to  $T$ .

$R$  is universal gas constant.

$u$  is specific internal energy and  $U$  is internal energy.

$v$  is specific volume.

$K$  is thermal conductivity coefficient.

$\dot{m}$  is mass flow rate.

$x_{st}$  is static mass quality.

$l$  is the active height of heat transfer which is common in all thermal layers.

## VI. INDICES

Subscripts w and f refer to water, g refers to vapor, fg refers to evaporation, a refers to air, sat refers to saturation condition, and superscripts t refers to time, and  $t+\Delta t$  is one time step beyond the timet.

## REFERENCES

- [1] Nuclear Power-The Environmentally Clean Option, Containment Isolation section, Westinghouse – AP1000-2007. <http://www.ap1000.westinghousenuclear.com/>.
- [2] Neil E. Todreas, Mujid S. Kazimi, NUCLEAR SYSTEMS 1 Thermal Hydraulic Fundamentals, Massachusetts Institute of Technology, HEMISPHERE PUBLISHING CORPORATION, 1990, Chapter 7, pp. 239-254.
- [3] Rahim, F. C., et al., A study of large break LOCA in the AP1000 reactor containment, Progress in Nuclear Energy (2011), doi:10.1016/j.pnucene.2011.07.004, pp. 132-137.
- [4] Frank P. Incropera (Book), Introduction to heat transfer, 4th Edition, 2002.
- [5] The AP1000 European DCD, UK AP1000 Safety, Security and Environmental Report (2007), Chapter 6, Section 6-2\_r1, Page 6.2-66, Table 6.2.1.3-9.
- [6] The AP1000 European DCD, UK AP1000 Safety, Security, and Environmental Report (2007), Chapter 6, Page 6.2-51, Table 6.2.1.1-2.
- [7] The AP1000 European DCD, UK AP1000 Safety, Security, and Environmental Report (2007), Chapter 6, Page 6.2-54, Table 6.2.1.1-8.
- [8] The AP1000 European DCD, UK AP1000 Safety, Security and Environmental Report (2007), Chapter 6, Section DECL.
- [9] The AP1000 European DCD, UK AP1000 Safety, Security and Environmental Report (2007), Chapter 3, Section 3-8\_r1, Page 3.8-175, Figure 3.8.4-1.